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MODELLING LIQUID STEEL MOTION CAUSED BY ELECTROMAGNETIC STIRRING IN CONTINUOUS CASTING STEEL PROCESS

MODELOWANIE RUCHU CIEKŁEJ STALI WYWOŁANE MIESZANIEM ELEKTROMAGNETYCZNYM W PROCESIE CIĄGŁEGO ODLEWANIA

The paper presents an attempt of modelling liquid steel motion triggered off by electromagnetic stirring. Steel viscosity was calculated on the basis of temperature field determined with the use of stationary heat conduction equation. Velocity field was determined using Navier-Stokes equations and stream continuity equation. Solution was obtained using the finite element method. The developed model allows to carry out quick simulating calculations of fluid flow. Stationary solution was employed, and this allowed to reduce computation time substantially.

Keywords: continuous casting, electromagnetic stirring, numerical modelling, finite elements method

W pracy podjęto próbę modelowania ruchu ciekłej stali wywołanej mieszaniem elektromagnetycznym. Lepkość stali obliczano na podstawie pola temperatury wyznaczonego ze stacjonarnego równania przewodzenia ciepła. Pole prędkości wyznaczono korzystając z równań Naviera-Stokesa i równania ciągłości strugi. Rozwiązanie uzyskano metodą elementów skończonych. Opracowany model pozwala na wykonywanie szybkich obliczeń symulacyjnych ruchów ciekłej stali. Zastosowano rozwiązanie stacjonarne, co umożliwiło istotne skrócenie czasu obliczeń.

1. Introduction

Continuous steel casting process is the method used to obtain semi-finished products that prevails all over the world. Numerical modelling of the discussed process has been intensified in recent years [1,2,3,4,5,6,7]. The models available in the market in majority are based on the use of commercial packages and numerical programs [1, 4]. However, using this type of software leads to excessively long numerical computation times.

Original applications created for the purposes of single process modelling do not have an option allowing to model large numbers of industrial processes. Their advantages are: high specialisation level, and model and solving method optimisation. They allow to obtain much shorter computation times and to use these applications for optimisation and controlling industrial process in almost real time.

Modelling continuous steel casting process requires to use mathematical models, which allow to determine temperature field and thermal as well as mechanical stresses induced by the band bending forward and back. However, these two basic models do not provide full process description. It is also essential to determine liquid steel motions in a mould and in liquid zone under the mould. Moreover, it is possible to use electromagnetic stirring resulting in cast strand structure homogenising.

The paper shows an attempt of modelling liquid steel fluid flow resulting from electromagnetic stirrer action, carried out using an original computer application. The finite element method has been used to obtain the solution.

2. Temperature field

Superheated liquid steel is transported via entry nozzle to the mold, which is intensely cooled with water, and takes heat from solidifying band. The discussed process involves heat transfer by conduction and convection. The former one occurs in solid body zone. In liquid zone both processes appear: heat conduction in liquid, and convective heat transport. Temperature field in solidifying band results from the impact of these two heat transport mechanisms, and it may be determined using stationary solution of heat convection and conduction equation [8]:

$$\int_V \left[\lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_v - \right. \\ \left. -\rho c \left(v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) \right] dV = 0 \qquad (1)$$

where:

T – steel temperature, K

λ – thermal conductivity of steel, W/(m K)

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ρ – steel density, kg/m^3
c – specific heat of steel, J/(kg K)
v_x, v_y, v_z – steel velocity field, m/s
q_v – internal heat source, W/m^3
The solution is temperature field T, which should meet boundary conditions on bloom surface.

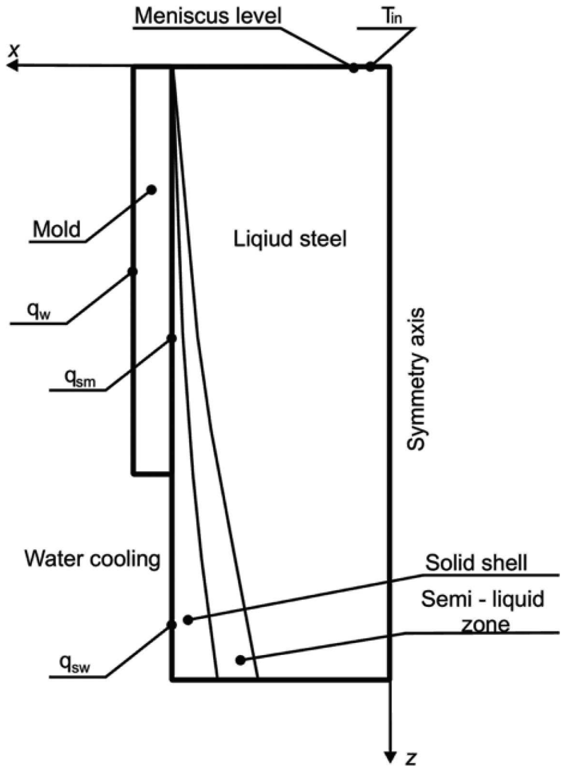

Fig. 1. Schema of the control volume and the boundary conditions applied in the thermal model

Boundary conditions (Fig.1) are applied in form of heat stream densities taken over on bloom surface in mold q_{sm}:

$$q_{sm} = \alpha_{sm} (T_s - T_m) \tag{2}$$

where:
α_{sm} – combined heat transfer coefficient, W/(m^2 K),
T_m – mold temperature, K,
T_s – steel temperature, K.
and after leaving mold q_{sw}:

$$q_{sw} = \alpha_{sw} (T_s - T_{ws}) \tag{3}$$

where:
α_{sw} – convection heat transfer coefficient for water spray cooling, W/(m^2 K).

In order to solve the bloom cooling issue, it is also required to determine mould surface temperature. This is possible by way of determining temperature field of mould, which on the inside takes over heat from bloom, and on the outside gives it up to water cooling system. Mould temperature field has been determined on the basis of heat conduction equation solution:

$$\frac{\partial T}{\partial \tau} = \frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{4}$$

for boundary condition on inside surface S_{sm}:

$$q_{sm} = \alpha_{sm} (T_s - T_m) \tag{5}$$

and on outside surface S_w cooled with water:

$$q_w = \alpha_w (T_{mo} - T_w) \tag{6}$$

where:
α_w – heat transfer coefficient for water cooling in mold channels, W/(m^2 K),
T_w – cooling water temperature, K.
T_{mo}– outside mold temperature, K

Solutions for equations (1-6) obtained using the finite element method have been discussed in detail in work [8].

3. Electromagnetic stirring

Flow effect of electromagnetically mixed and heated liquid metal is described by Navier-Stokes, Maxwell's, Ohm's and thermal equations, all nonlinear, linked through electro-magnetic and dynamic forces, and heat transfer by convection and conduction [9,10,11,12]. The basic feature of model is that in most cases not magnetic field density, but electric current density is used as the basic electromagnetic variable.

It was assumed for calculation purposes that incompressible fluid conducting heat in presence of magnetic field, gravity and heat source would flow steadily through the mould. Mould wall thickness was omitted. Ohm's law determines electric current distribution:

$$J = \sigma (-\nabla\varphi + V \times B) \tag{7}$$

where:
J – electric current density, A/m^2
B – magnetic induction, T
σ – electrical conductivity, S/m
Magnetic field may be divided into:

$$B = B_0 + B_1 \tag{8}$$

where:
B_0 – apply field, T
B_1 – field induced by the electric current J, T
Taking into account Biot-Savart law – volumetric integral throughout liquid area:

$$B_1 (J) (x) = -\frac{\mu_e}{4\pi} \int_V \frac{x - y}{|x - y|^3} \times J (y) dy \tag{9}$$

As a result we obtain:

$$F = J \times (B_0 + B_1 (J)) \tag{10}$$

where:
F – force induced by the electromagnetic stirrer, N

Heat release resulting from friction and Joule-Lenz law is small compared to heat transfer by convection and penetration, and it may be omitted in temperature distribution calculations.

On the basis of the above approach, the finite element method was employed to simulate flow of liquid metal whirling steadily in a uniform magnetic field perpendicular to mould axis. The researchers prepared a procedure library in

Fortran 99, allowing to build a system of linear equations and to determine field of electromagnetic forces in element joints in electromagnetic stirrer work area and its vicinity (within range of induced magnetic field). Mesh generator used in numerical computations allows to carry out free cast strand digitising with possibility to concentrate network of elements in vicinity of mould walls.

Set of results contains x and y coordinates and the values of total force generated by electromagnetic stirrer. Figure 2 shows boundary conditions employed in the model and the scheme of division into elements for $^1/_4$ of cross-section.

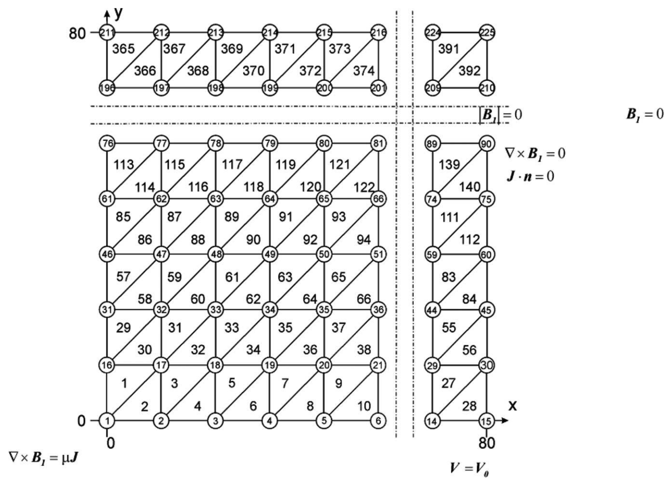

Fig. 2. Scheme of the control volume and boundary conditions applied in the electromagnetic model

Using electric current density instead of magnetic field density as primary electromagnetic variable allows to avoid artificial and idealised boundary conditions for electric and magnetic fields.

Obtained force field allows to determine velocity field in cross-section of the modelled cast strand using Navier-Stokes and continuity equations [13]:

$$\begin{aligned}
\frac{dv_x}{d\tau} &= X - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2}\right) \\
\frac{dv_y}{d\tau} &= Y - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu}{\rho}\left(\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2}\right) \\
\frac{dv_z}{d\tau} &= Z - \frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\mu}{\rho}\left(\frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}\right) \\
&\left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}\right) = 0
\end{aligned} \tag{11}$$

where:

p – hydrostatic pressure, Pa,

X, Y, Z – mass forces, m/s^2,

μ – dynamic viscosity of steel, kg/(m s),

Boundary conditions for velocity field assume velocity zero value for direction tangential to cast strand surface. Computations were carried out for the whole cast strand cross-section. Solutions for equations (11) obtained using the finite element method have been discussed in work [14].

In order to reduce time required for computations, the temperature field and force and velocity field values were determined separately. The first stage involved calculation of temperature field assuming average casting speed in the whole modelled area ($v_z = v_c$, $v_x = v_y = 0$). Force field and velocity field values were determined for temperature field obtained in this way. In the developed model, liquid steel parameters depend on chemical constitution and temperature. Viscosity and density are the basic parameters describing properties of each liquid. Temperature field value is entered into the module taking into account temperature impact on steel viscosity. Changes in liquid steel viscosity with temperature are shown in diagram (Fig. 3). Changes in liquid steel density in temperature function are shown in diagram (Fig. 4).

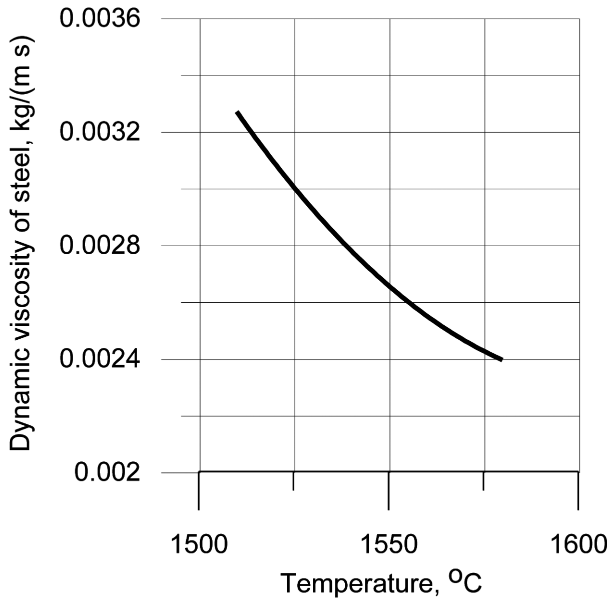

Fig. 3. Liquid steel viscosity [13]

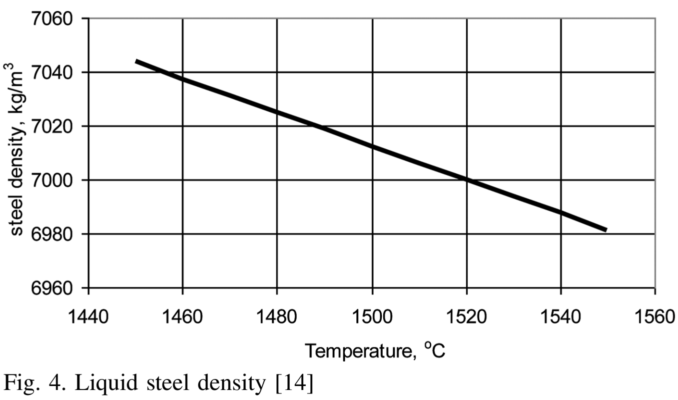

Fig. 4. Liquid steel density [14]

Temperature field determined from equation (1) allows to divide the modelled area into three zones: liquid, semi – liquid and solidified. Properties in semi – liquid zone are determined on the basis of solid body and liquid steel fraction.

4. Numerical computations

The analysis covered continuous casting process for steel containing 0.2% of carbon, in rectangular mould sized 160 mm×160 mm (cross-section) and round mold sized ∅ 160 mm. Solidus and liquidus temperature values for the examined steel were 1380°C and 1450°C, respectively. Liquid steel casting temperature was 1480°C. Casting speed in both cases: 0.06 m/s. The researchers carried out numerical simulation of continuous steel casting process using an electromagnetic stirrer. Data taken for computations were as follows: stirring current frequency: 5 Hz, induction inside stirring area: 0.05 Tesla, stirring current: 300A. Geometrical parameters of electromagnetic stirrer: length: 0.2 m, distance between stirrer beginning and liquid steel meniscus: 0.9 m. Computations related to temperature field and velocity field carried out using a computer equipped with Pentium IV 3.2 GHz processor take approximately 15 min. Figure 5 and 6 shows cast strand temperature field determined using equation (1) for both cases. Broken line indicate liquidus and continuous line indicate solidus temperatures.

Completed simulation allowed to obtain distribution of force field inside the mould and velocity field in liquid metal subjected to electromagnetic stirring. Figure 7 and 8 shows force field resulting from the impact of applied magnetic field generated by electromagnetic stirrer. Magnetic field decreases with penetration depth in both cases, which is shown in the picture by decreasing lengths of force vectors while moving further from cast strand surface towards its axis.

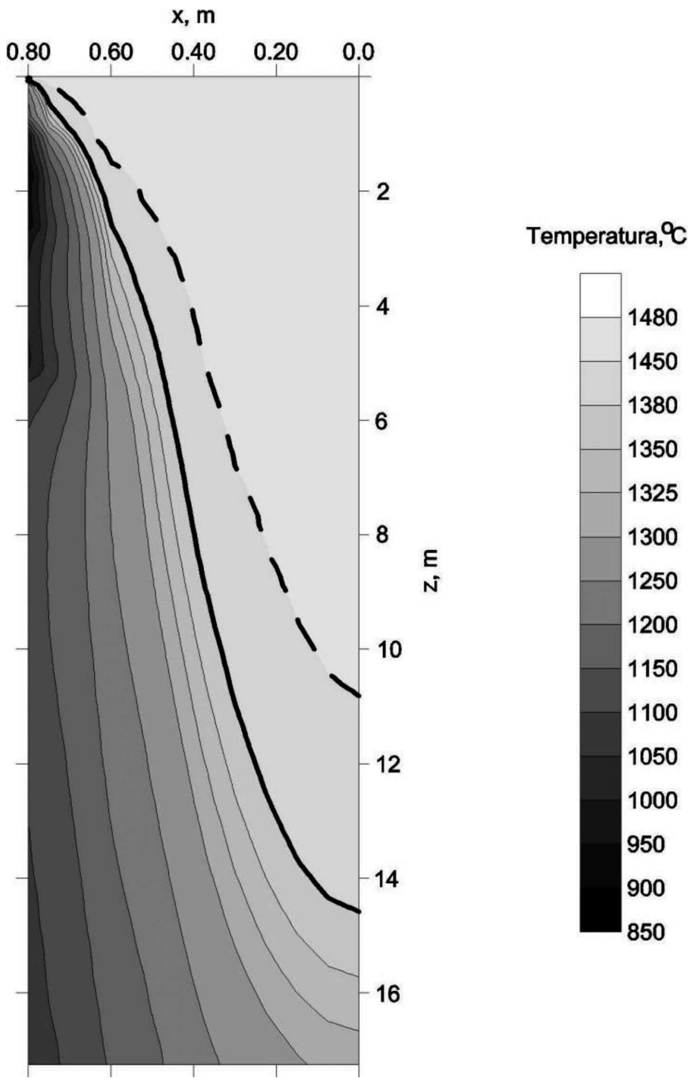

Fig. 5. Temperature field in *longitudinal section* for 160×160 ingot

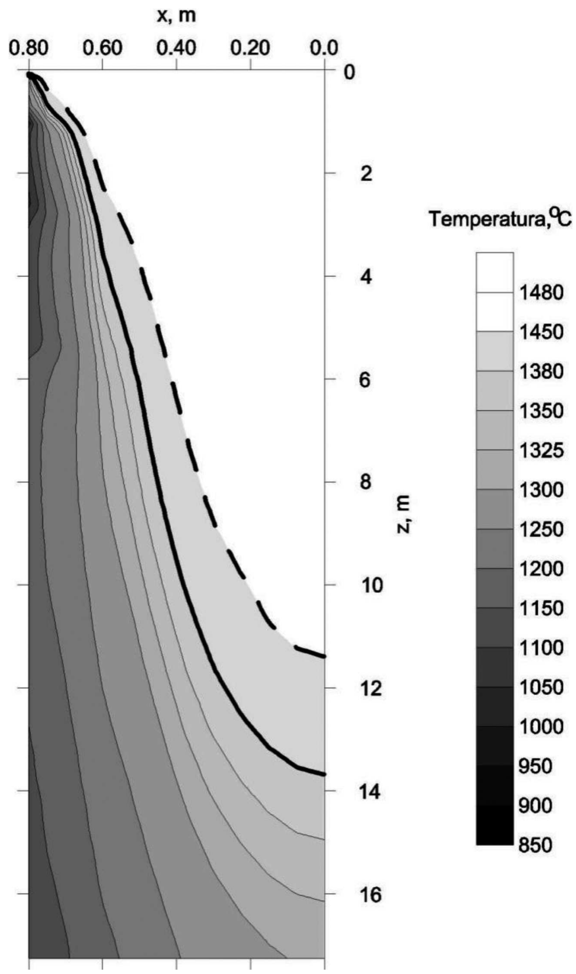

Fig. 6. Temperature field in *longitudinal section* for ∅ 160 ingot

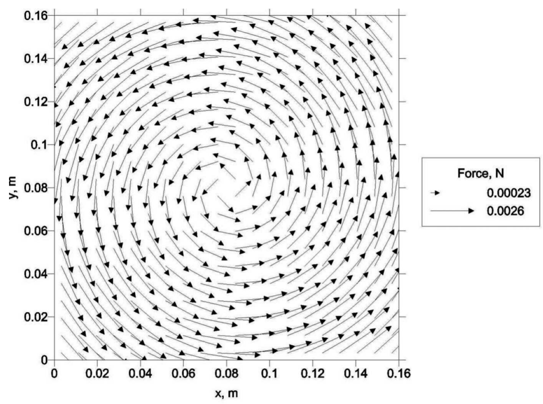

Fig. 7. Force field in the cross section – 160×160 ingot

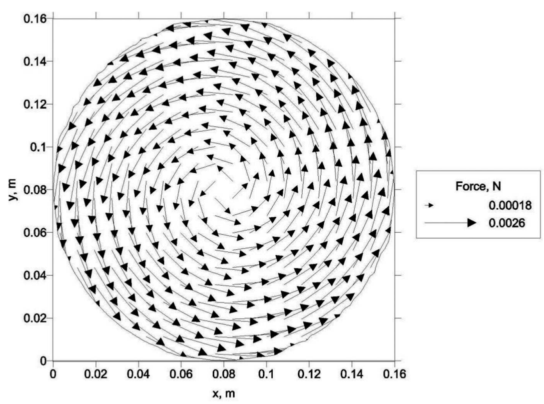

Fig. 8. Force field in the cross section – ∅ 160 ingot

Figure 9 and 10 presents liquid steel velocity at the distance of 1 m from meniscus, in liquid billet in secondary cooling area (in cast strand cross-section), reached as a result of forces generated by electromagnetic stirrer.

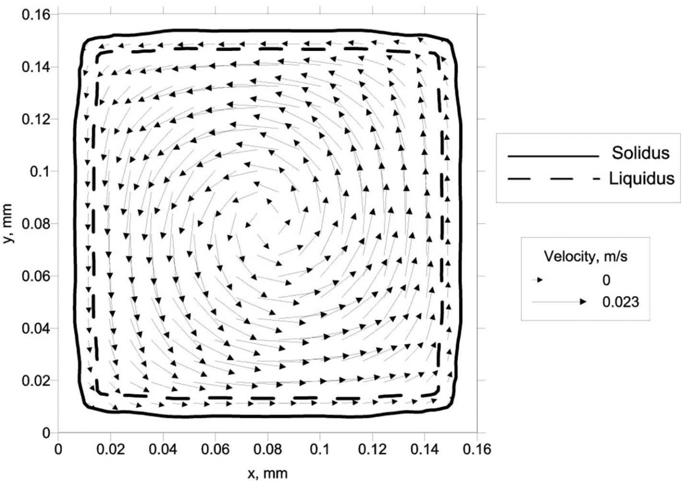

Fig. 9. Velocity field in the cross section – 160×160 ingot

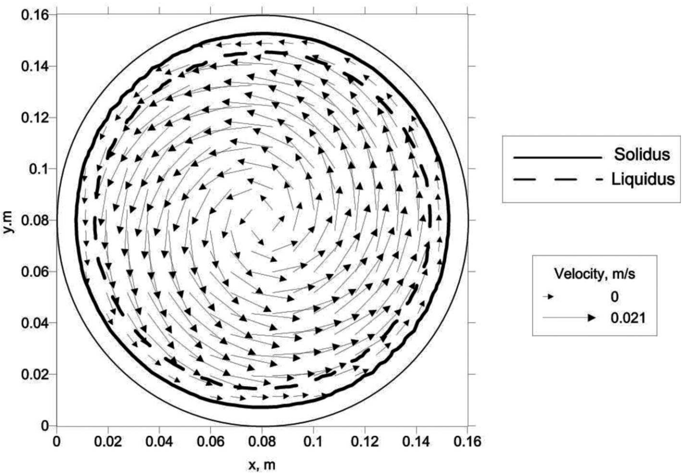

Fig. 10. Velocity field in the cross section – ∅ 160 ingot

Velocity value is lowest near solidified zone due to growing solid phase fraction. In liquid core zone velocity values are dropping while approaching modelled area centre. This results from drop of forces generated by electromagnetic stirrer.

Induction stirring in metallurgical processes allows to obtain the following results: good process economics, guarantee of repeatable product and manufacturing process quality, and safety of work. At the same time all equipment is easy to operate. Currently, simulations may be used as a tool for predicting metallurgical outcomes in COS installations.

5. Summary

The developed model allows to determine liquid steel velocity field resulting from electromagnetic stirring impact. Short time required for computations makes it easier to use this model to design electromagnetic stirrer systems. In the model the researchers analysed forces and velocity field generated by installing an electromagnetic stirrer. As a result of difficulty in acquisition of experimental data for the modelled process, evaluation of obtained results is mainly based on comparisons with existing data available in literature.

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REFERENCES

[1] J. Jowsa, W. Derda, M. Warzecha, T. Merder, I. Staniewski, A. Cwudziński, Modelowanie numeryczne wymiany masy, ciepła i pędu podczas ciągłego odlewania stali i w procesach metalurgii pozapiecowej. Hutnik – Wiadomości Hutnicze **6**, 252-256 (2006).

[2] M.A. Ruhul, A. Mahajan, Modeling of turbulent heat transfer during the solidification process of continuous castings. Journal of Materials Processing Technology **174**, 155-166 (2006).

[3] Y.H. Man, G.L. Hyun, H.S. Seung, Numerical simulation of three- dimensional flow, heat transfer, and solidification of steel in continuous casting mold with electromagnetic brake. Journal of Materials Processing Technology **133**, 322-339 (2003).

[4] M. Rywotycki, K. Milkowska-Piszczek, L. Trebacz, Identification of the boundary conditions in the continuous casting of steel. Archives of Metallurgy and Materials **57**, 385-393 (2012).

[5] Z. Malinowski, T. Telejko, B. Hadała, Influence of heat transfer boundary conditions on the temperature field of the continuous casting ingot. Archives of Metallurgy and Materials **57**, 325-331 (2012).

[6] M. Hojny, M. Głowacki, The methodology of strain – stress curves determination for steel in semi-solid state. Archives of Metallurgy and Materials **54**, 2, 475-483 (2009).

[7] L. Sowa, A. Bokota, Numerical model of thermal and flow phenomena the process growing of the cc slab. Archives of Metallurgy and Materials **56**, 2, 359-366 (2011).

[8] B. Hadała, Z. Malinowski, Accuracy of the finite element solution to steady convection-diffusion heat transport equation in continuous casting problem. Informatyka w Technologii Materiałów **9**, 302-307 (2009).

[9] A. Meir, P. Schmidt, S. Bakhtiyarov, R. Overfelt, Velocity, Potential, and Temperature Distributions in Molten Metals During Electromagnetic Stirring, Part II: Numerical Simulations, Fluids Engineering Division FED-Vol. 249, 1999.

[10] The Casting Volume, Hanley P.J., Kollberg S.G., Electromagnetic Methods for Continuous Casting, The AISE Steel Foundation, Pittsburgh 2003.

[11] M. Janik, H. Dyja, Problemy Modelowania COS z uwzględnieniem mieszania elektromagnetycznego i ruchu ciekłej fazy, II Międzynarodowa Konferencja Ciągłe odlewanie stali, Krynica, 131-138 (2006).

[12] Pei-Bai Zhou, Numerical Analysis of Electromagnetic Fields, Springer-Verlag, Berlin Heidelberg 1993.

[13] J. Malczewski, M. Piekarski, Modele procesów transportu masy pędu i energii. PWN, Warszawa 1992.

[14] M. Rywotycki, Z. Malinowski, T. Telejko, Wpływ prędkości odlewania na pole temperatury pasma COS.

KomPlasTech 2006 Informatyka w technologii metali. XIII konferencja, Szczawnica, 119-126 (2006).
[15] G. K n i a g i n i n, Staliwo - Metalurgia i Odlewnictwo. Śląsk, Katowice 1972.
[16] J. T h e r e t, G. L e s o u l t, Deroulement de la solidification des fonts a graphite spheroidal. Hommes et Fonderie, Fevrier **4**, 19-30 (1984).

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